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Squeeze Casting of Aluminium Metal Matrix Composites- An Overview

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Abstract

Squeeze casting is the combination of the casting and forging processes that can be done with help of high pressure when it is applied during melt solidification. Applying pressure on the solidification of molten metal could change melting point of alloys which enhances the solidification rate. Moreover it refines the micro and macrostructure; it is helpful to minimize the gas and shrinkage porosities of the castings. This paper stresses the importance of squeeze casting of the Aluminium Metal Matrix Composites in all aspects: squeeze pressure, casting (melt)/ preform preheat/ die temperature, solidification rate, reinforcement particle sizes, porosity and mechanical properties.

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Keywords: *Squeeze casting; Aluminium metal matrix composite; mechanical properties.*

1. Introduction

Composite materials are gaining wide spread acceptance, due to their characteristic behavior and high strength-to-weight ratio. Of these Aluminium metal matrix composites are finding increased applications, because of their improved mechanical and tribological properties. The fabrication techniques of MMC's play a major role in the improvement of the mechanical and tribological properties [27, 28]. Among the available casting techniques, squeeze casting has the following major advantages: (i) the parts produced are without gas porosity or shrinkage porosity; (ii) feeders or risers are not required, and therefore no metal wastage occurs; (iii) alloy fluidity (castability) is not critical in squeeze casting, as both common casting alloys and wrought alloys can be squeeze cast to finished

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shape with the aid of pressure, and (iv) squeeze castings can have mechanical properties as good as wrought products of the same composition [20]. Squeeze casting is an attractive processing method for producing Aluminium MMC's as they exhibit better mechanical properties due to the presence of fewer common defects such as porosity and shrinking cavities, and the elimination of segregation of the reinforcement [5, 17]. Squeeze casting employs low die filling velocity, with minimum turbulence and high-applied pressure, to produce good quality products [40]. There are two different forms of squeeze casting, i.e., direct SC and indirect SC. In the direct squeeze casting process, the pressure is applied on the entire surface of the liquid metal during solidification by a punch, which produces castings of full density. In the indirect squeeze casting process, the metal is injected into the die cavity by a small diameter piston [24]. In the casting of metal matrix composites, the dispersion of the reinforcement particles within the matrix plays an important role in achieving the desired properties in the material [6]. The wettability of the reinforcement particles in molten metal is improved by applying high pressures during casting [15].

1.1 *Squeeze Pressure:*

In squeeze casting, the applied pressure improves the wettability and the bonding force between the Al alloy/SiCp [15, 26]. The applied pressure has an undercooling effect which, together with the loss of heat through the dies, favours rapid solidification. The high pressure also discourages the nucleation of gas bubbles [29]. The high pressure further reduces the size of the gas bubbles, but may be absorbed into the solution and disappear in a bubble free casting. Applied pressure on primary α phase can decrease the grain size and secondary dendrite arm spacing (SDAS). The pressure is applied to gain the largest melt undercooling, so that the nucleation rate can be increased exponentially when the melt temperature in the die was lower than the liquidus temperature. When the higher cooling rate and large undercooling effect are applied on melt there would be expected refinement change in structure of the squeeze cast samples. There are two core constituents in the microstructure of squeeze cast sample. At first, it has α phase identified as light dendritic areas; next the darker areas shown in micrographs due to the effect of a eutectic matrix of the α phase and silicon particles. Following Fig.1 shows of the main two constituents in the microstructure of each sample include a primary α (Al rich) phase seen as light dendritic areas, and a eutectic matrix of the α phase and silicon particles seen as darker areas in the micrographs. Closer views of the eutectic regions of the samples are shown in Fig.1, where the changes in the morphology of the eutectic silicon particles on increasing the applied pressure can be easily recognized [3]. Due to the undercooling, the contact time between the reinforced particles and the molten aluminum was shortened, and this decreased the possibility of interfacial reactions [5]. For both the Al alloy and the composites, a squeeze pressure of the order of 100 MPa is found to be sufficient to get the microstructural refinement, to reduce these porosities, and obtain a complete contact between the metal and the die surface.

Table1. Summary of author's conclusion on optimum selection of squeeze pressure

SI. NO	Material-Alloy/Composite	Reinforcement Particle Size	Optimum Pressure (Mpa)	Time Duration (Sec)	Reference Number's
1	LM 6		140 MPa		14
2	LM 13		100 MPa		3
3	LM 13		100 MPa		31
4	LM 25		100 Mpa	60 Sec	32
5	5083 Al		100 Mpa		33
6	Al–Zn–Mg–Cu alloy		160 Mpa	120 Sec	34
7	SiC/Gr/Al, Alloy: 2024 Al	SiC : 3µm &40% Gr : 3%, 5%, 7% & (1,6,10,20,70 µm)	100 MPa	180 Sec	5
8	Al 2124 alloy & Al 2124-10%SiC_p	SiC :23µm	100 MPa	120 Sec	6
9	Al_2O_3/A356	Al_2O_3	100 MPa	180 Sec	30
10	a) Al-15%SiC_p b) A 356/SiC_p	SiC_p	100 MPa	30 Sec	26

Using squeeze casting assisted pressurization for the infiltration of the SiC particle preforms with high purity Al, the formation of Al_4C_3 is widely prevented, owing to the peculiarities of the squeeze casting process, which does not provide favourable thermodynamic and kinetic conditions for the associated reaction in equation (1) to proceed [13].

$$4Al + 3SiC \rightarrow Al_4C_3 + 3Si \quad (1)$$

Due to the cooling effect of the preform and the mold, the contact time between the reinforced particles and the molten aluminium was shortened, and this decreased the possibility of interfacial reactions. In another method, when the SiC perform had been preheated to 600°C, which induces the formation of SiO_2 oxidation layers on the SiC particles. The SiO_2 layers prevent any direct contact between the SiC and the molten Al, and this inhibits the formation of Al_4C_3 [5].

If the DAS of the matrix is very close to the reinforcement particle size, the particle becomes immobile because the movement restriction provided by the matrix network results in the better distribution of the particles. Therefore, the combined effect of the high cooling rate and significant reduction of the DAS (24µm, which is comparable to the particle size of the SiC used) achieved by the application of pressure has enabled the improved distribution of SiC_p [6].

Finally, squeeze pressure plays a major role in the decrease of grain size, SDAS, reduction of porosity, increase in the heat transfer coefficient, preventing Al_4C_3 formation and microstructural refinement. Table.1 shows the optimum pressure obtained by other authors for squeeze castings of Al alloys/Composites as 100 Mpa.

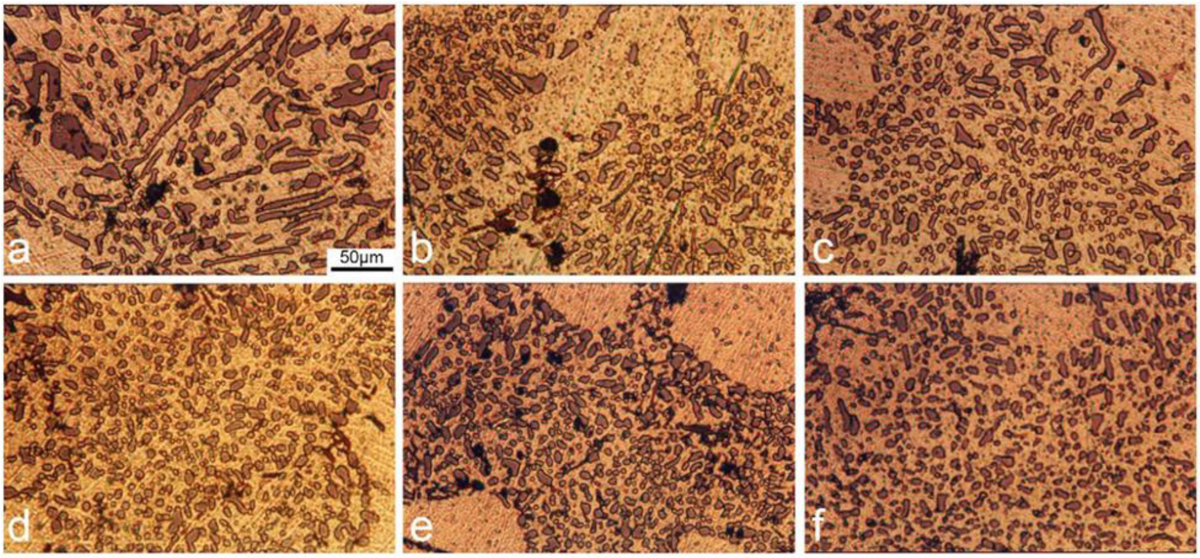

Fig.1- Effect of external pressure on the morphology of eutectic silicon particles of squeeze cast LM13 alloy: (a) 0 (Atmospheric Pressure), (b) 20 MPa, (c) 53 MPa, (d) 106 MPa, (e) 171 MPa (f) 211 MPa (T_m = 730 ° C and T_d = 200 ° C). [3]

1.2 Casting (melt) / Preform preheat / Die temperature:

Casting temperature has an effect on the mechanical properties of squeeze cast aluminium metal matrix composites. Theoretically, the largest melt undercooling would be achieved, if the pressure were applied when the melt temperature in the die was lower than its liquidus temperature, and just above the temperature required for the explosion of nucleation (i.e. about 0.98 of the melting point of the alloy in the case of heterogeneous nucleation).

When the melt temperature was lowered from 780 to 730°C and then to 680°C, the macrostructures gradually became finer, and the grains became smaller. However, further decrease of the melt temperature to 630°C results in the formation of very fine and uniform equiaxed grains [31]. It is established that to ensure successful preform infiltration, a preform temperature of 600°C or above is necessary [19]. For the squeeze casting of the aluminium alloy, the best melt temperature to use was either 690 or 660°C; the former would give a better property at the top of the casting while the latter, at the bottom of the casting [20]. As the die temperature increases, the primary α-Al particles become coarse and more globular, and the average particle diameter (APD) continuously increases while the average particle size (APS) initially increases and later decreases. When the die temperature reaches 350°C, there are many rosette particles; therefore, the shape factor ASF suddenly decreases. It is seen that, the tensile strength and elongation increased rapidly as the die temperature increased from 200°C to 250°C, but only slightly altered with the die temperature between 250 and 300°C. However, the tensile strength and elongation decreased suddenly as the die temperature increased to 350°C [38]. The optimum levels of the process parameters to obtain a good surface finish of the SC components of LM6 aluminium alloy, are a squeeze pressure of 140 N/mm^2, and die preheating temperature of 250°C [14].

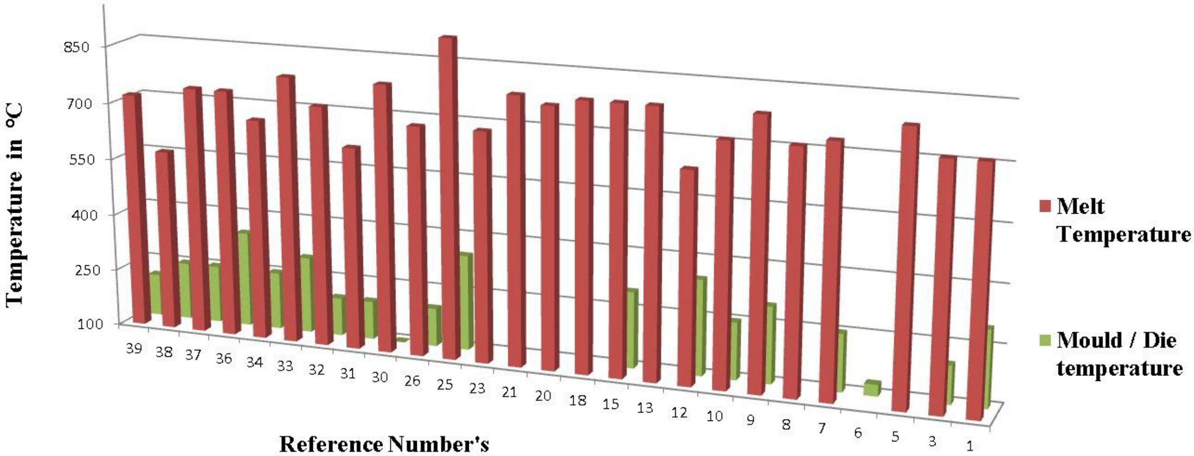

Fig.2 Casting (Melt) temperature and Die temperature for Squeeze Casting

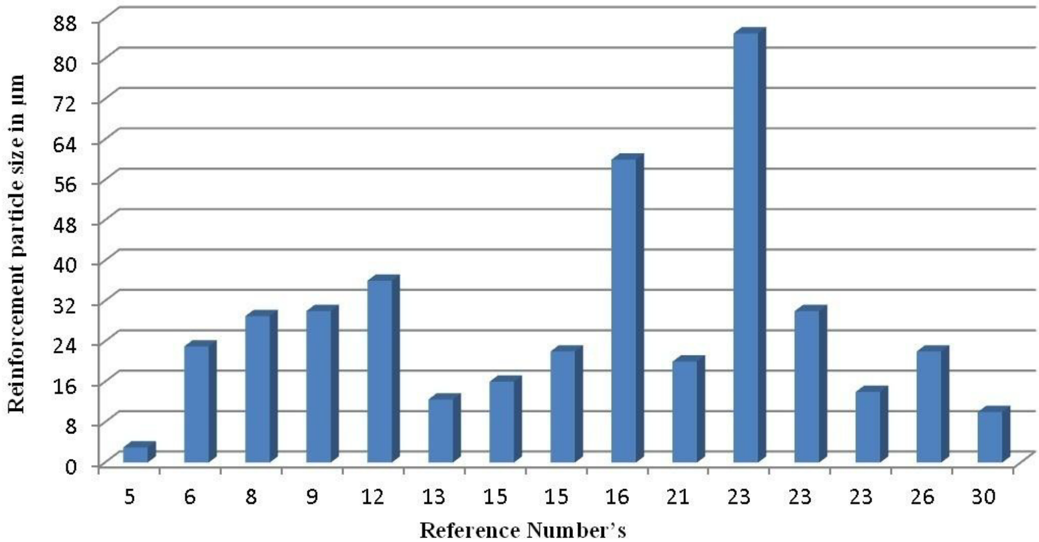

Fig.3 Reinforcement particle size for Squeeze Casting

The significant change is made on the SDAS of the primary α phase and eutectic silicon particles by the melt temperature. Their functions reduce with a decrease in the melt temperature by the effect of higher solidification rate resulting for the expected microstructures [3]. There is an increase in grain size with the increase in melt temperature which is usually attributed to a lower cooling rate during solidification. It was mentioned that a sudden large undercooling could be created in the melt upon application of pressure, if the melt temperature and timing of pressure application were accurately controlled. A decrease in the melt or die temperature rendered similar effects as that of increasing the external pressure on the macrostructure and hardness. This is due to the increased cooling rate during the solidification of the squeeze casting [31].

Here, Fig 2 represents the various authors' selections of Cast (melt) temperature and Die temperature for Squeeze Casting of Aluminium alloy/Composites. We can conclude that the optimum range for melt temperature in Squeeze Casting process can be 600°C - 700°C, and the die temperature range can be around 250°C.

1.3 Solidification rate:

The solidification rate was very high in squeeze cast composites, so serious agglomerations have not been observed. Failures in composites occur simultaneously in both the matrix and SiC particles, implying that there is a good bonding between the matrix and the particles [12]. The relation between the grain size "d" and the cooling rate "R" is written as:

$$dR^a = K \tag{2}$$

where K and d are constants, "a" is a factor which depends on the type of composite and is in the range of 0.34 to 0.39; this also shows that the grain size increased when the cooling rate decreased [30]. The shorter the solidification time, the higher is the value of the property [39]. The interface heat transfer coefficients were found to increase with the increase in applied pressure.

A simple law which correlates the mechanical properties (yield strength and Vickers hardness) with cooling can be extracted from the scientific literature. First, the average grain size can be correlated to the mechanical properties by Hall-Petch (Reed Hill, 1996):

$$\sigma_y = \sigma_0 + K_Y \lambda^{-1/2} \tag{3}$$

$$HV = HV_0 + K_H \lambda^{-1/2} \tag{4}$$

Furthermore, a relationship between the cooling rate (ε) and the average dendrite cell size (λ) is:

$$\lambda = B\varepsilon^n \tag{5}$$

Combining Eqs. (3), (4) and (5) a direct correlation between the cooling rate and both the final yield strength and hardness is obtained:

$$\sigma_Y = \sigma_0 + C_Y \varepsilon^m \quad \text{where} \quad \begin{cases} C_Y = K_Y B^{-1/2} \\ m = -\dfrac{n}{2} \end{cases} \tag{6}$$

$$HV = HV_0 + C_H \varepsilon^m \quad \text{where} \quad C_H = K_H B^{-1/2} \tag{7}$$

The material constants of Eqs. (3–7) were extracted from the laboratory tests on small specimens for the EN-AB46000 aluminium alloy [35, 36]. The higher cooling rate coupled with large under cooling, caused significant improvement in the microstructure. The previous studies indicate that as the applied pressure increases the cooling rate increases, and reaches an optimum value corresponding to a pressure level of about 100 MPa, for both the alloy and the composite. At higher pressure levels, the under cooling may also be large enough, so that the combined effect of the under cooling and higher cooling rate is reflected in the refinement of the microstructure [5].

The applied pressure leads to the decrease in the grain size and the DAS of the primary α phase. This applied pressure influences the as-cast microstructure in two different ways. This effect can be justified by the equation (8):

$$P = P_0 \exp\left(\frac{-\Delta H_f}{RT_f}\right) \tag{8}$$

where ΔH_f is the latent heat of fusion, and P_0 and R are the constants. Increasing the pressure (P) causes an increase in the freezing point (T_f) of the alloy. The higher freezing point brings about larger undercooling in the initially superheated alloy, and thus elevates the nucleation frequency, resulting in a more fine-grained structure. Furthermore, the fine-grained structure is possibly due to the elevated cooling rate, which is related to the higher heat transfer coefficient, when the melt and the die wall are intimately contacted [34].

Squeeze casting at a higher pressure of 100 MPa keeps the melt and the die in close contact throughout the solidification, due to which a better solidification range can be achieved.

1.4 Reinforcement particle sizes:

The flexural strength of the composites increased as the reinforcement particle size was reduced for the same volume fraction of SiC_p. The smaller particle sizes will provide more interfacial area, which serves as the nucleation sites for grain formation. When the particle size is smaller, the spacing between the particles is reduced. The smaller particles will exert more constraint on grain growth during cooling, and more restriction on plastic flow during deformation, which can also contribute to the increase in strength [23].

An increased packing fraction can be obtained, by mixing particles that have a proper particle size distribution, because fine particles can pack more efficiently around larger ones. Even a very high packing fraction of more than 90% could be achieved by mixing the proper volume fraction of different particle sizes, that differed by several orders of magnitude. On this basis, three average particle sizes of 20, 40 and 60 μ mm were used, and they were divided into three groups: (i) 20 μ mm SiC; (ii) 20 μ and 40 μ mm SiC with a weight ratio of 3:2; and (iii) 20 μ mm and 60 μ mm SiC with a weight ratio of 4:1 [21].

As shown in Fig 3, the Selection of the refinement particle grain size (SiC_p) in μm for squeeze casting of Aluminium composites was important, from which the optimum reinforcement particle grain size of SiC_p in the range of 15–30 μm was considered for squeeze casting. This is due to the higher particle size which reduces the nucleation sites during solidification, and a weaker interfacial bond strength which becomes the crack initiation site in the composites.

1.5 Porosity and Mechanical properties:

Refinement in the microstructure is clearly visible with the increase of the applied pressure [6]. The applied pressure increases the volume fraction of the Al-rich α-phase, and decreases in the size of the primary Al-rich dendrites [37]. The microstructures of the squeeze cast specimens, prepared under higher applied pressures, are much finer. Increasing the freezing point brings about undercooling in an initially superheated alloy, and thus increases the nucleation frequency; causing a finer grain size structure [22]. The heat transfer and cooling rate increase as the applied pressure increases and, as a result, the primary α-Al particles become smaller and closer to a spherical shape [38]. Furthermore, the fine grained structure observed in the squeeze casting specimens seems to be due to the increase in cooling rate that occurs by the higher heat transfer coefficient, as a result of the intimate contact between the melt and the die wall. Applying pressure on the melt in the squeeze casting process has increased the cooling rate values, and thus seems to be the main reason for grain refinement of the alloy microstructure [7].

To gain the expected mechanical properties of squeeze samples, the thermal modification is a process that is created to provide a change in the solidification rate and higher undercooling of the melt. The tensile strength of the SiC/Gr/Al composites clearly depends on the volume fraction, and particle size of graphite; and the elastic modulus is also affected remarkably by the volume fraction and size of the graphite particles [5]. The strength of the material will decrease as with the grain size increases. In addition, a large sized eutectic silicon phase will degrade the strength of the composites, since the silicon phase is brittle, so that cracks will first generate in the silicon, and then propagate rapidly through the Al_2O_3 particles or the matrix, leading to the composite failure [30].

The squeeze pressure increases the mechanical properties and reaches a maximum value at a pressure of 100 MPa, beyond which the increase in properties is negligible [6]. The finer microstructure due to higher cooling rates seemed to be the cause of the increase in tensile properties [7]. The grain size of the alloy decreases obviously on increasing the applied pressure, which can be clearly characterized by the secondary dendritic arm spacings (SDAS) [10]. The hardness value is higher when the melt temperature is 630°C; that is, when the grain size is the smallest. There is no significant change in the hardness value, when the melt temperature is above 680°C [31]. The wettability and the bonding force between Al alloy/SiCp were improved by the applied pressure, and the tensile strength was also increased by approximately 10% [26].

The dendritic growth is a result of the concentration gradients set up in the melt when solidification takes place too rapidly, for equilibrium to exist between the die and the melt. These non-equilibrium concentration gradients lead to thermal undercooling, which encourages the growth of secondary and tertiary arms from the crystal surfaces. The dendrite sizes produced by the squeeze-casting process were by far the finest of the three processes considered, this being due to the rapid solidification rate produced by the higher heat-transfer coefficient of the steel dies and the high squeeze pressure of the process [32].

The dendrite arms were broken, and a fine-grained equiaxed microstructure was obtained by squeeze casting [12]. Decreasing the particle size of the reinforcement phase leads to better mechanical properties [15]. The addition of SiC whiskers and SiC nano particles to 2024 Al alloy increases its elastic modulus and strength. On increasing the content of the SiC nano particles, the strength of the composite increases further [18].

2. Conclusion:

In many research papers on optimization of process parameters in squeeze casting of aluminium alloys/composites have discussed the development of squeeze casting process for the advanced materials. From those papers the following conclusions have been drawn:

1. The optimum pressure used in the squeeze casting of Aluminium alloys and composites, which gives a better microstructural refinement and increase in the mechanical properties, is 100 MPa.
2. The selection of the reinforcement particle size also influences the strength of the material in the squeeze casting process. The smaller the grain size the better the improvement in the properties.
3. The suggested melt and die temperature during the squeeze casting of Aluminium alloys and composites are 600°C to 700°C and around 250°C respectively.
4. There is a refinement in the microstructure with the combined effect of undercooling and a higher cooling rate, due to the high pressure level in the squeeze casting process.
5. The mechanical properties are enriched for both the alloys and the composites when fabricated through the squeeze casting technique, under controlled process parameters.

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